Locating the critical end point and the phase boundary of QCD from first principle QCD

Jan M. Pawlowski

Universität Heidelberg & ExtreMe Matter Institute

Beijing, July 13th 2024

for the fQCD collaboration

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

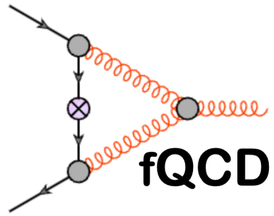
STRUCTURES CLUSTER OF EXCELLENCE

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

isoQuant SFB1225

EMMI

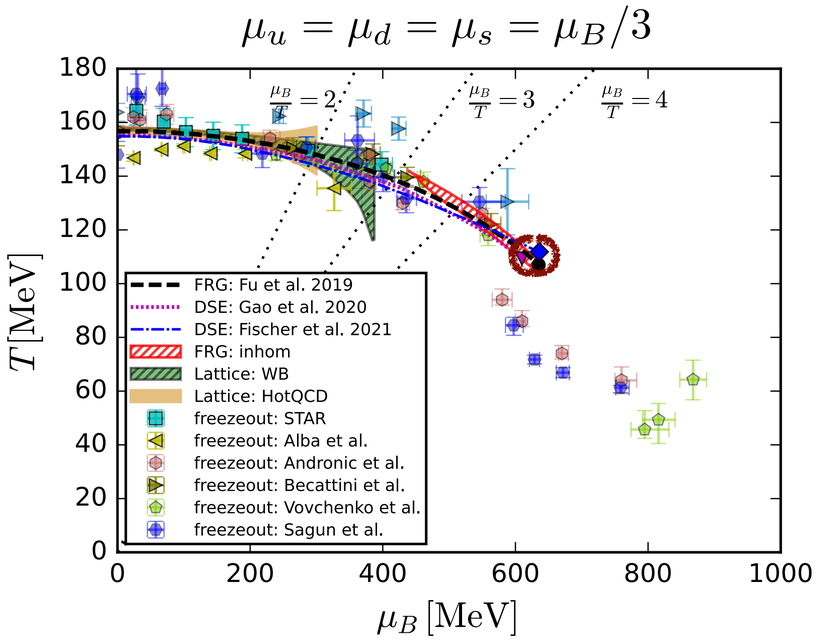
fQCD collaboration



Dalian, Beijing, Darmstadt, Heidelberg, Gießen

Braun, Chen, Fu, Gao, Geissel, Huang, Lu, Ihssen, Pawlowski, Rennecke, Sattler, Schallmo, Stoll, Tan, Töpfel, Turnwald, Wessely, Wen, Wink, Yin, Zheng, Zorbach

Phase structure of QCD and the CEP



Functional QCD: CEP estimate

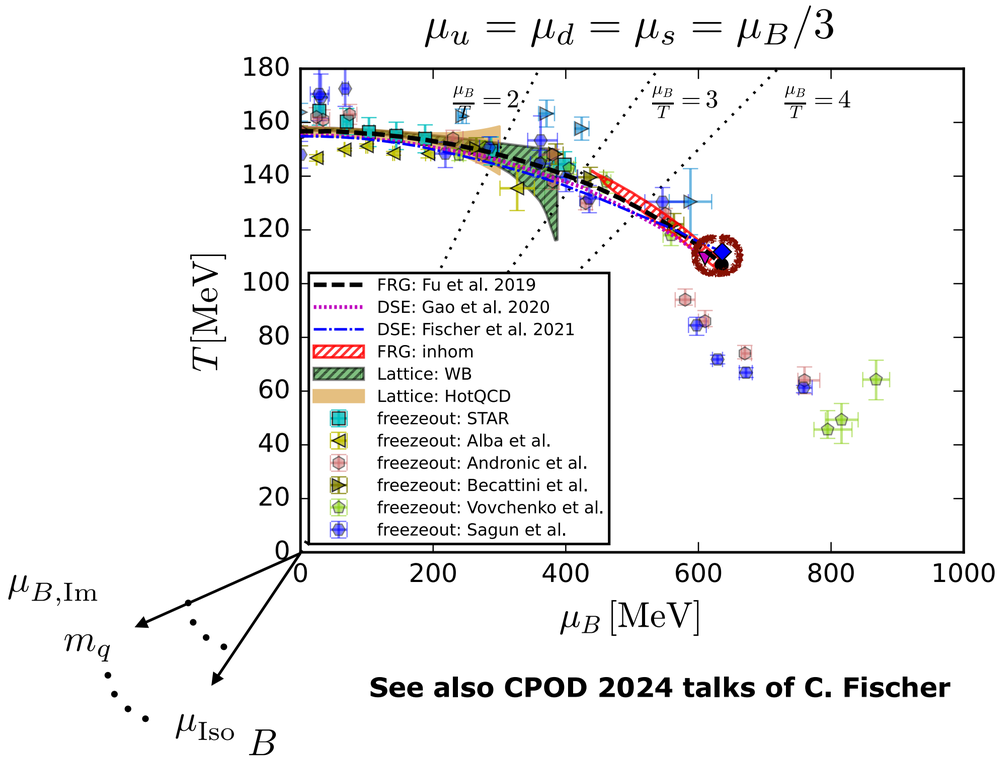
fRG: **Fu, JMP, Rennecke, PRD 101 (2020) 054032**

DSE: **Gao, JMP, PLB 820 (2021) 136584**

Gunkel, Fischer, PRD 104 (2021) 054022

$$(\mu_B\,,\,T)_{\mathrm{CEP}} \sim (600-650\,,\,105-115)\ \mathrm{MeV}$$

Phase structure of QCD and the CEP



See also CPOD 2024 talks of C. Fischer

Collect all possible information/structure for physics understanding & extrapolations

Functional QCD: CEP estimate

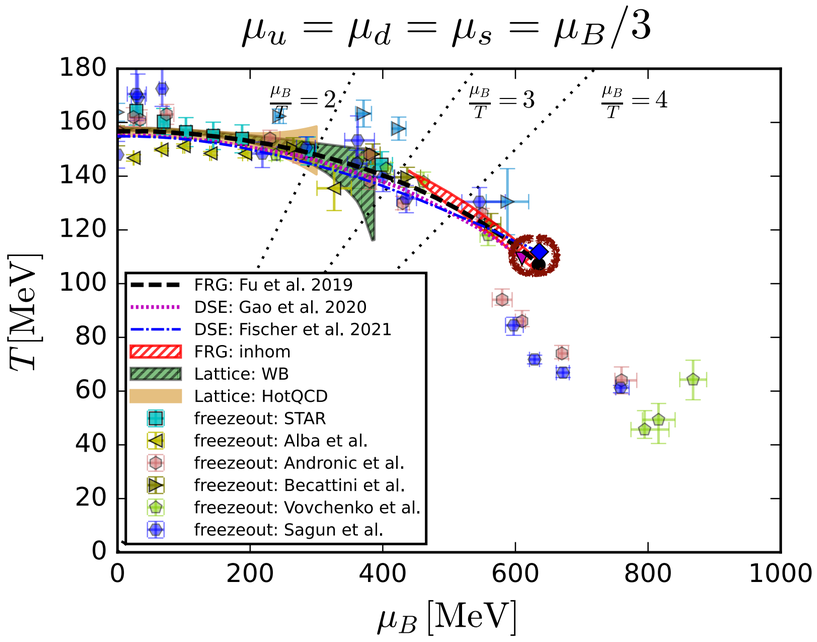
fRG: **Fu, JMP, Rennecke, PRD 101 (2020) 054032**

DSE: **Gao, JMP, PLB 820 (2021) 136584**

Gunkel, Fischer, PRD 104 (2021) 054022

$$(\mu_B\,,\,T)_{\mathrm{CEP}} \sim (600-650\,,\,105-115)\ \mathrm{MeV}$$

Phase structure of QCD and the CEP



Functional QCD: CEP estimate

fRG: **Fu, JMP, Rennecke, PRD 101 (2020) 054032**

DSE: **Gao, JMP, PLB 820 (2021) 136584**

Gunkel, Fischer, PRD 104 (2021) 054022

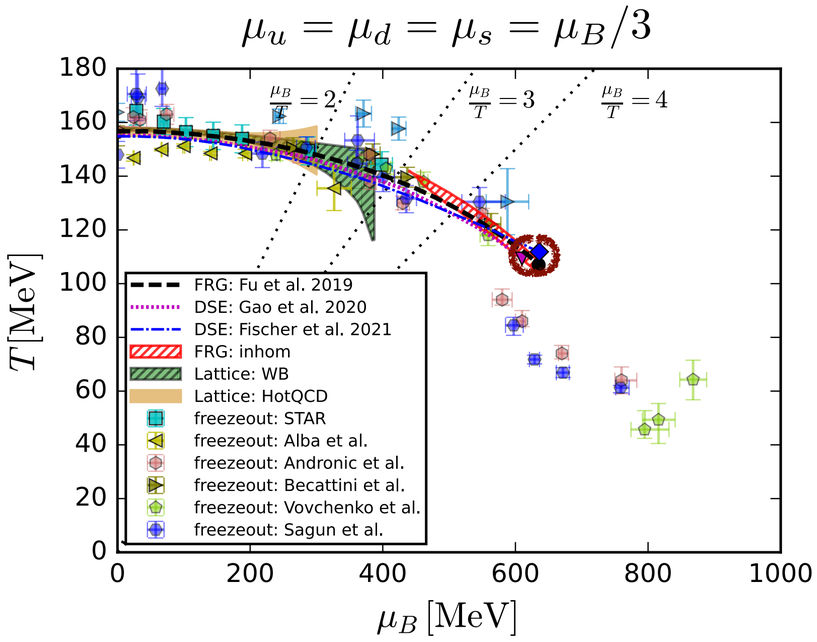
$$(\mu_B\,,\,T)_{\rm CEP} \sim (600-650\,,\,105-115)\ {\rm MeV}$$

Estimates & predictions

Requires computations in 1st principle QCD at

$$(\mu_B\,,\,T) \;\sim\; (\mu_B\,,\,T)_{\rm CEP}$$

Phase structure of QCD and the CEP



Functional QCD: CEP estimate

fRG: **Fu, JMP, Rennecke, PRD 101 (2020) 054032**

DSE: **Gao, JMP, PLB 820 (2021) 136584**

Gunkel, Fischer, PRD 104 (2021) 054022

$$(\mu_B\,,\,T)_{\rm CEP} \sim (600-650\,,\,105-115)\ {\rm MeV}$$

Estimates & predictions

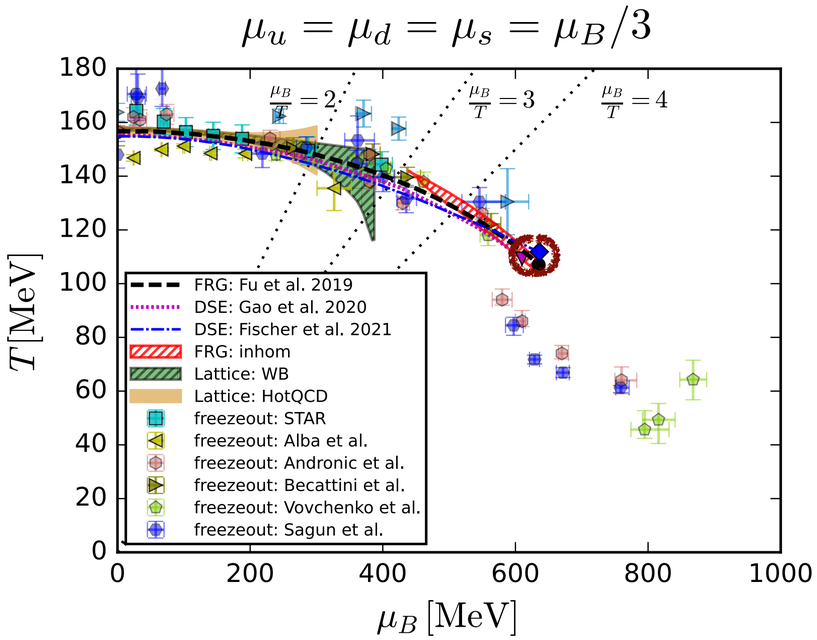
Requires computations in 1st principle QCD at

$$(\mu_B\,,\,T)\ \sim\ (\mu_B\,,\,T)_{\rm CEP}$$

Extrapolations for Pheno

Requires a discussion of the explicit & implicit assumptions

Phase structure of QCD and the CEP



Functional QCD: CEP estimate

fRG: Fu, JMP, Rennecke, PRD 101 (2020) 054032

DSE: Gao, JMP, PLB 820 (2021) 136584

Gunkel, Fischer, PRD 104 (2021) 054022

$$(\mu_B\,,\,T)_{\rm CEP} \sim (600-650\,,\,105-115)\ {\rm MeV}$$

Estimates & predictions

Requires computations in 1st principle QCD at

$$(\mu_B\,,\,T) \;\sim\; (\mu_B\,,\,T)_{\rm CEP}$$

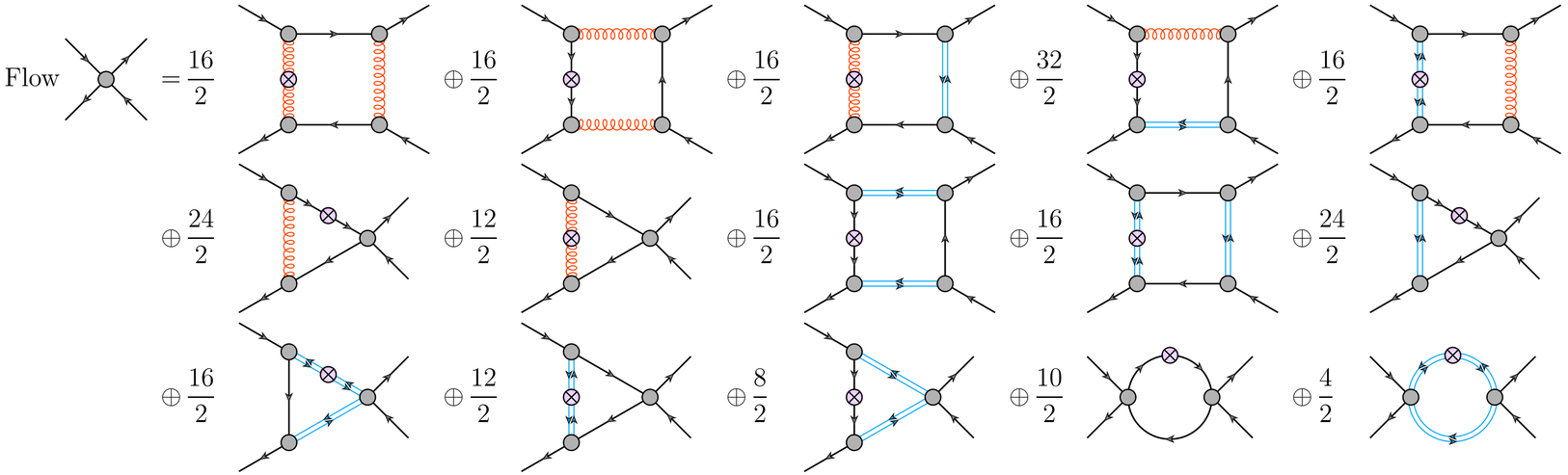
Extrapolations for Pheno

Requires a discussion of the explicit & implicit assumptions

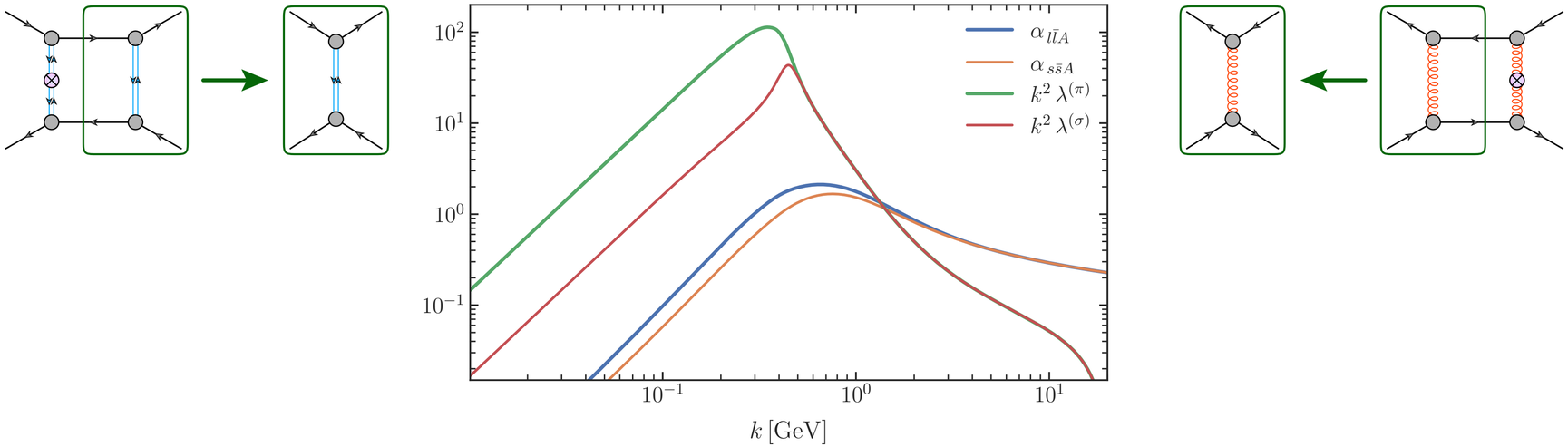
Lattice extrapolations

low energy effective theories: QM, NJL, PQM, PNJL, …, Holography

Functional QCD: systematic error estimates & the LEGO® principle

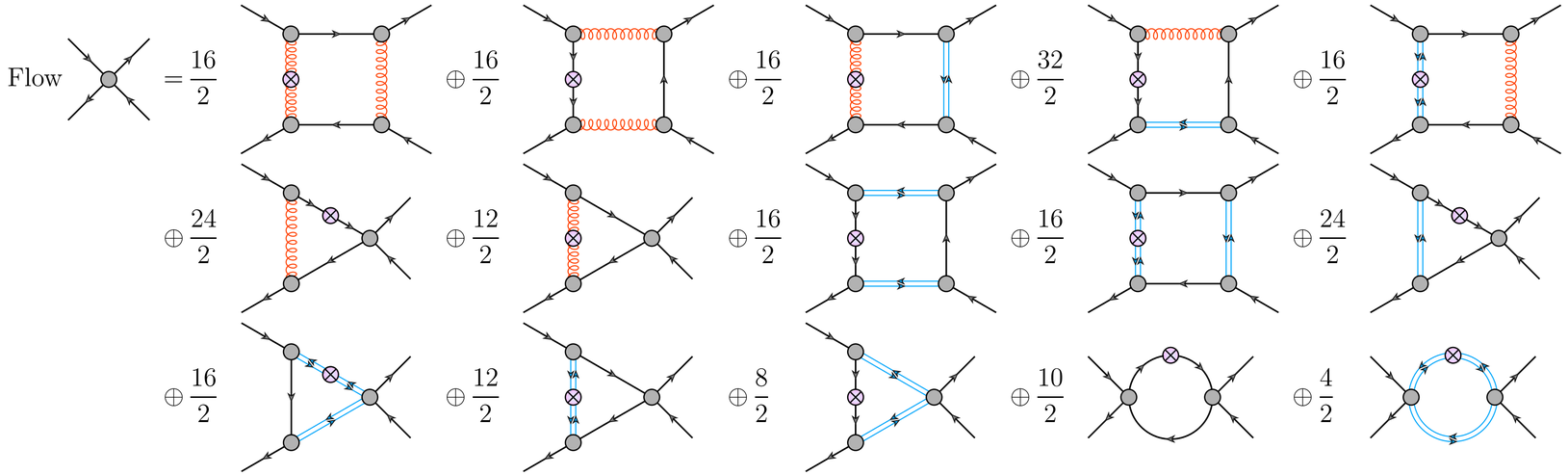


Example: 4-quark scattering vertex

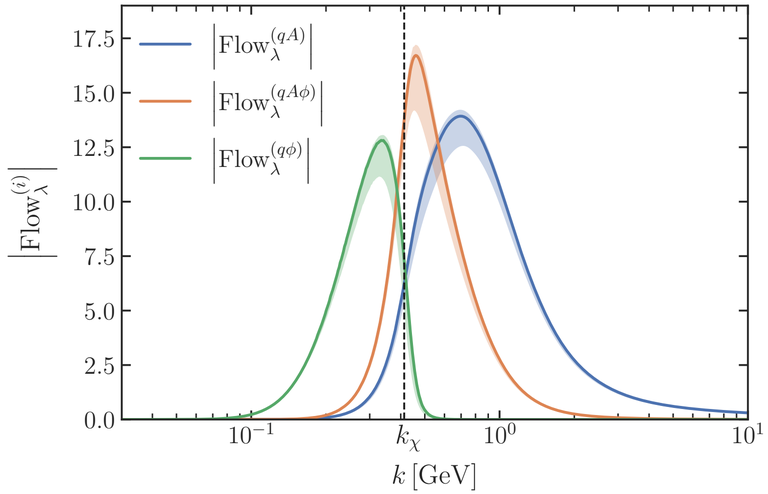


Ihssen, JMP, Sattler, Wink, in preparation

How to: systematic error estimates & the LEGO® principle

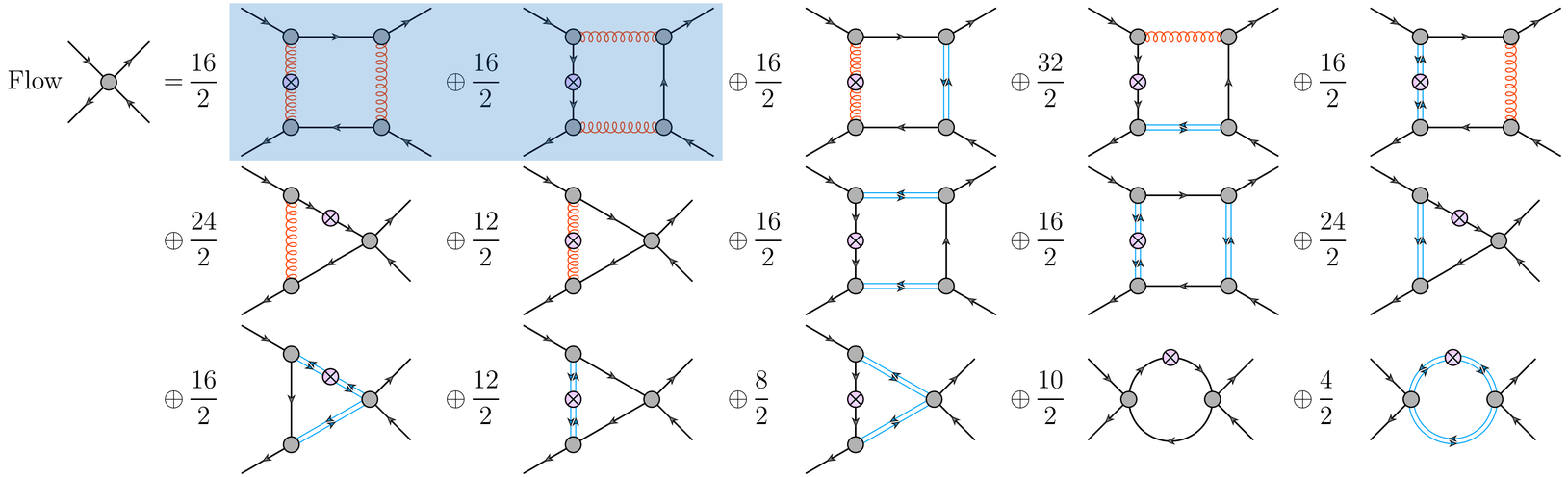


Example: 4-quark scattering vertex

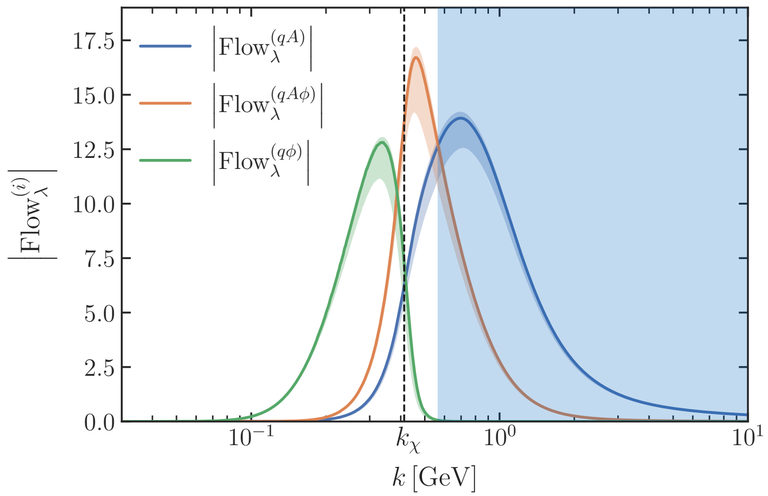


Ihssen, JMP, Sattler, Wink, in preparation

How to: systematic error estimates & the LEGO® principle

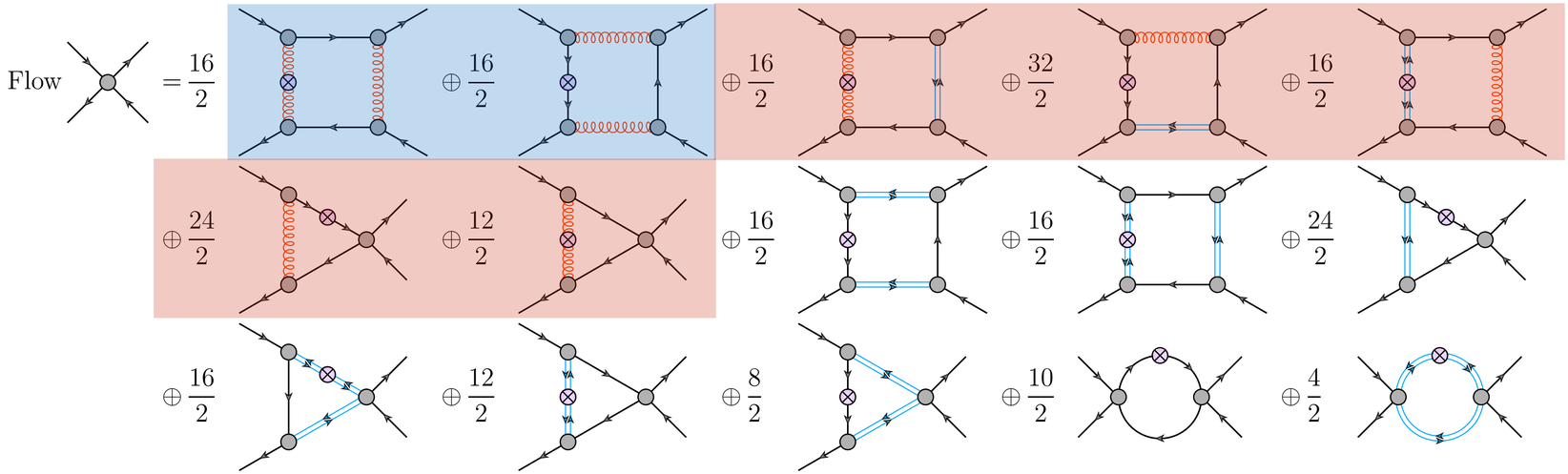


Example: 4-quark scattering vertex

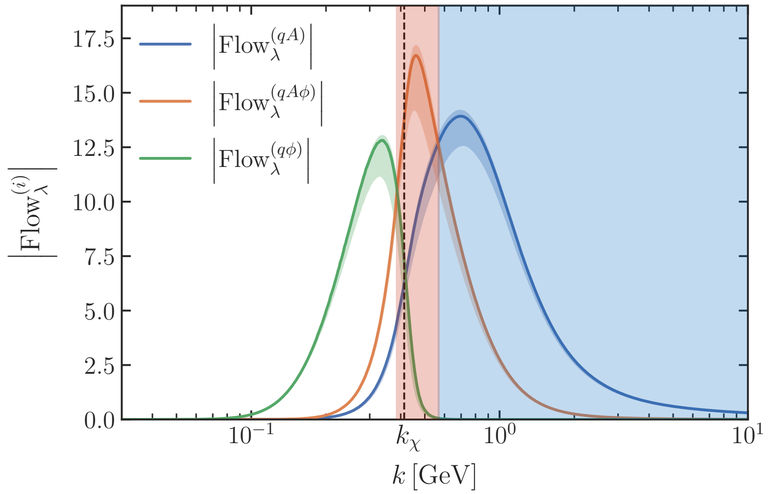


Ihssen, JMP, Sattler, Wink, in preparation

How to: systematic error estimates & the LEGO® principle

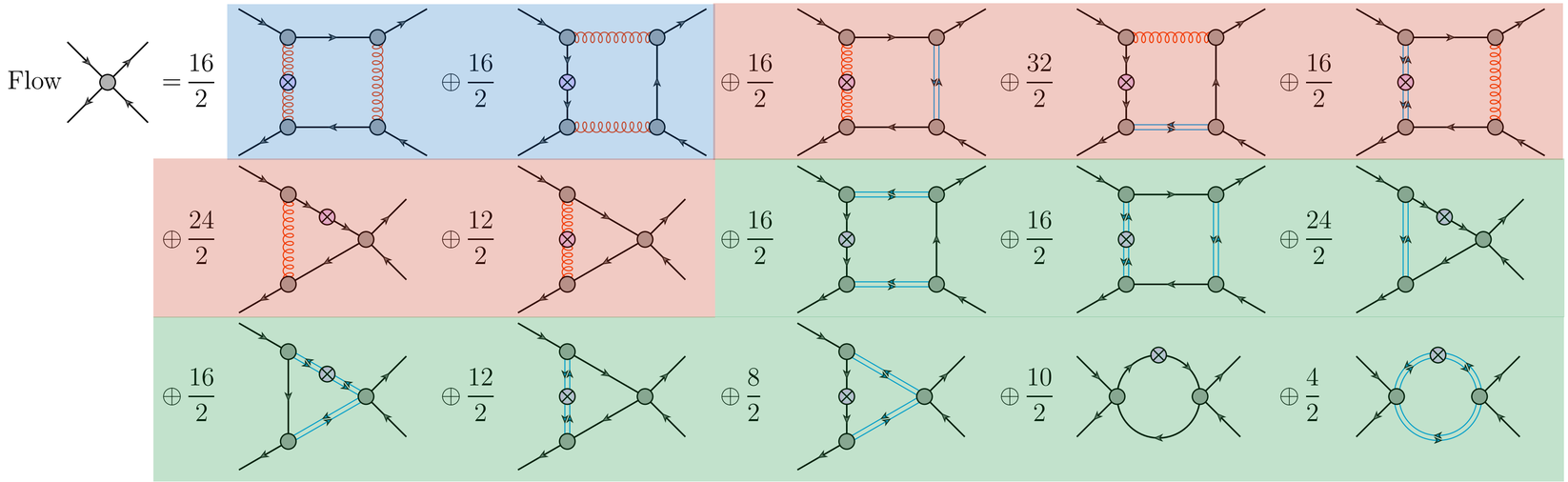


Example: 4-quark scattering vertex

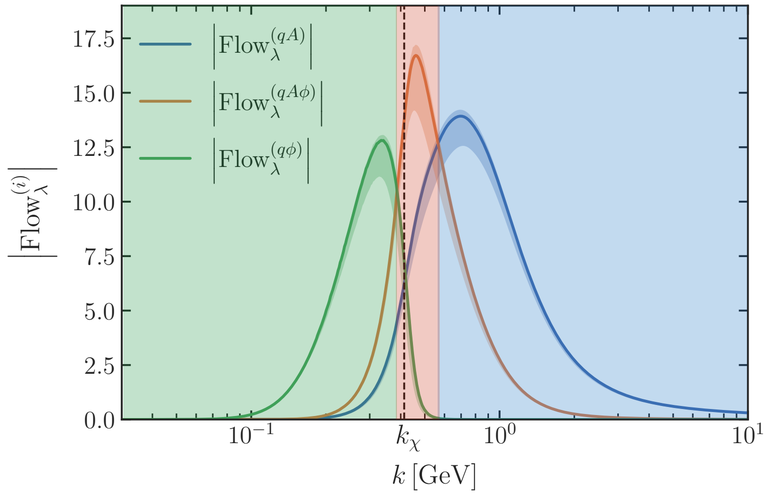


Ihssen, JMP, Sattler, Wink, in preparation

How to: systematic error estimates & the LEGO® principle

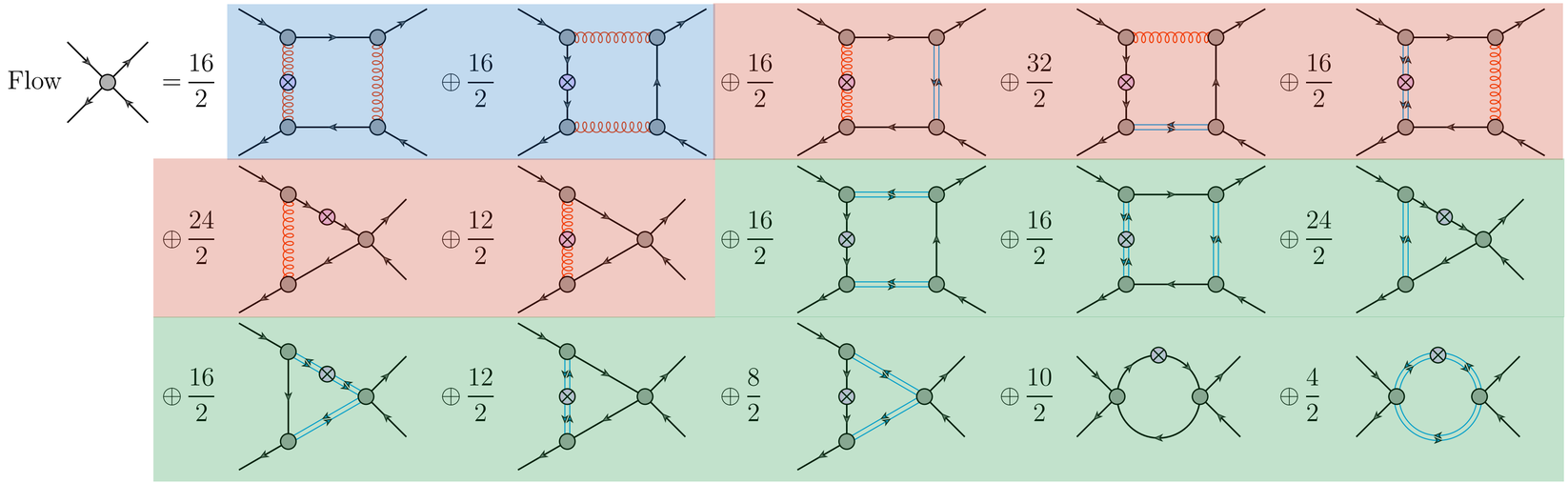


Example: 4-quark scattering vertex

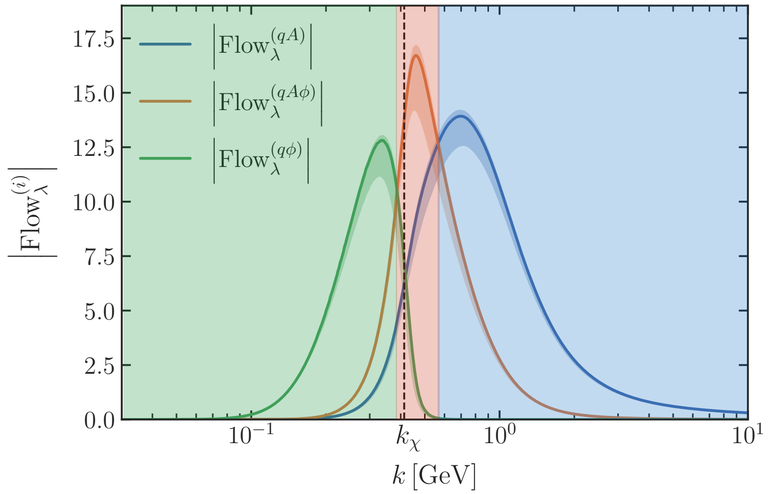


Ihssen, JMP, Sattler, Wink, in preparation

How to: systematic error estimates & the LEGO® principle



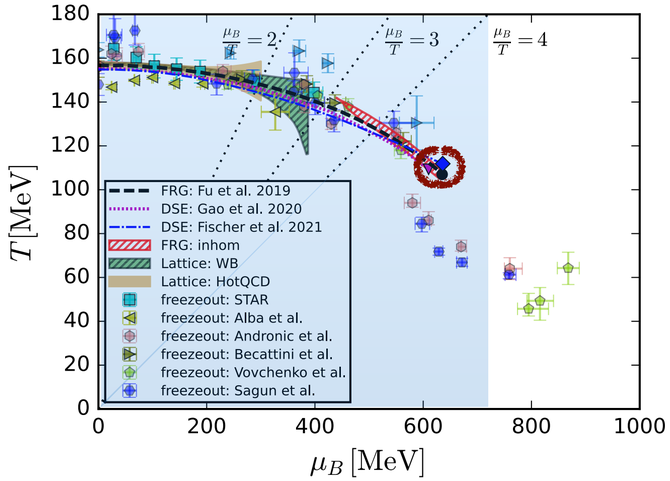
The unreasonable effectiveness of low energy effective theories



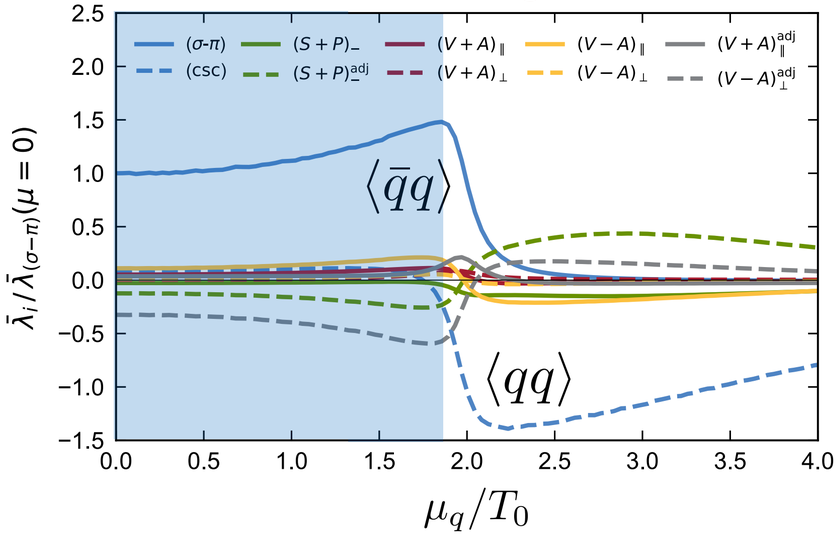
Access and combined use of error estimates from functional QCD & LEFTs

Ihssen, JMP, Sattler, Wink, in preparation

Predictions, estimates & extrapolations and how to use them



Four-quark scattering channels



Braun, Leonhardt, Pospiech, PRD 101 (2020) 036004

Dominance of scalar-pseudoscalar fluctuations

Pions & sigma mode

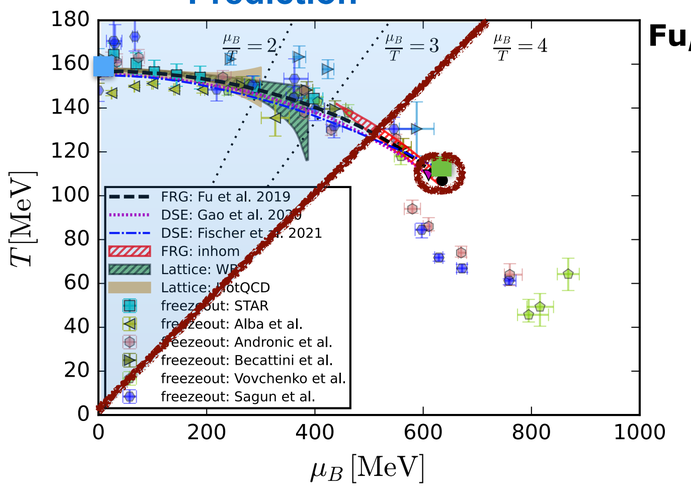
Predictions & estimates

Moat regime

Pisarski, Rennecke, PRL 127 (2021) 152302

see talk of Fabian Rennecke

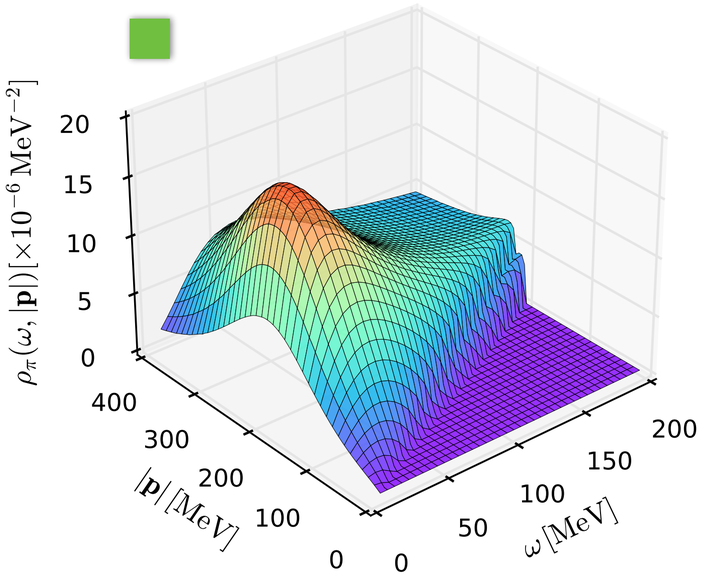
Prediction



Fu, JMP, Rennecke, PRD 101 (2020) 054032

Regime of quantitative reliability of current best truncation

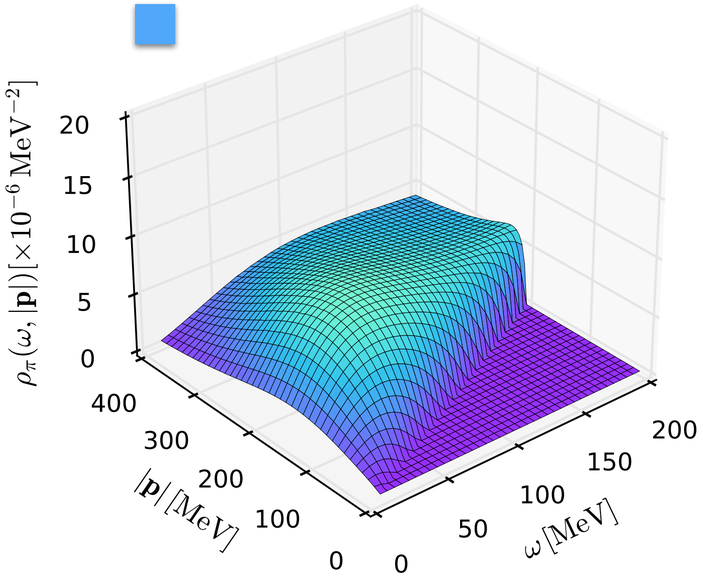
T=114 MeV & μ_B =630 MeV



Pion spectral functions

Fu, JMP, Pisarski, Rennecke, Wen, Yin, in prep

T=160 MeV & μ_B =0 MeV



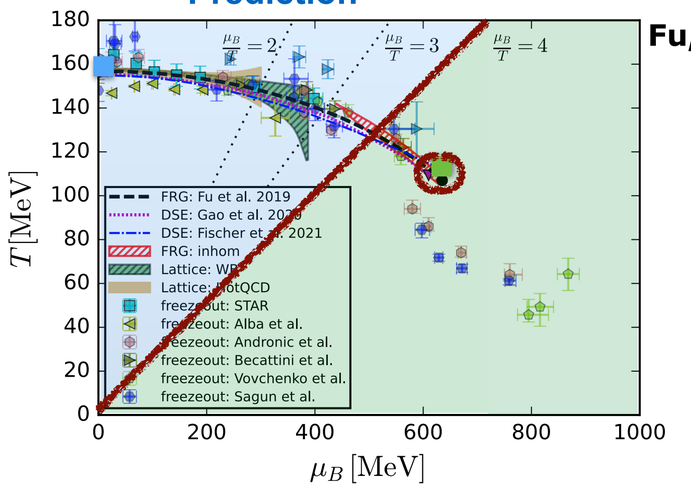
Predictions & estimates

Moat regime

Pisarski, Rennecke, PRL 127 (2021) 152302

see talk of Fabian Rennecke

Prediction

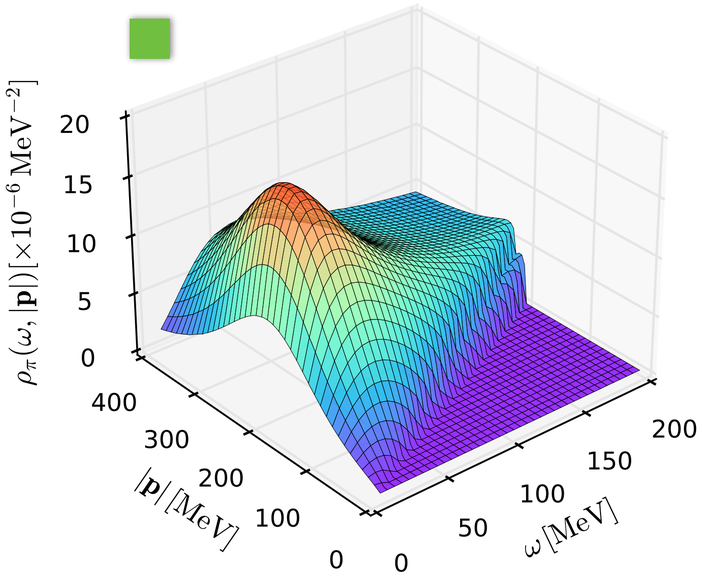


Fu, JMP, Rennecke, PRD 101 (2020) 054032

Regime of quantitative reliability of current best truncation

Estimate

T=114 MeV & μ_B =630 MeV

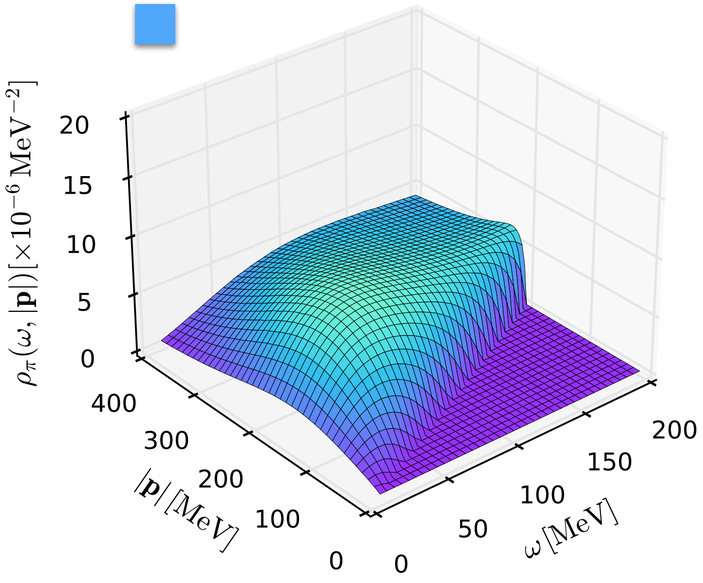


Moat regime is not captured quantitatively

Pion spectral functions

Fu, JMP, Pisarski, Rennecke, Wen, Yin, in prep

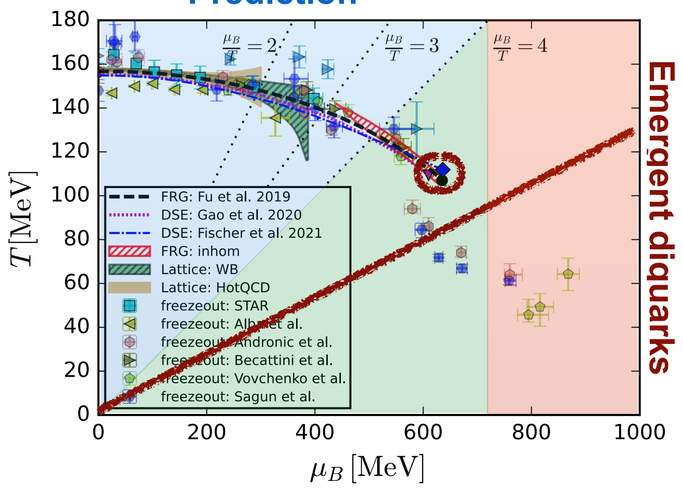
T=160 MeV & μ_B =0 MeV



Predictions & estimates

Emergent diquarks

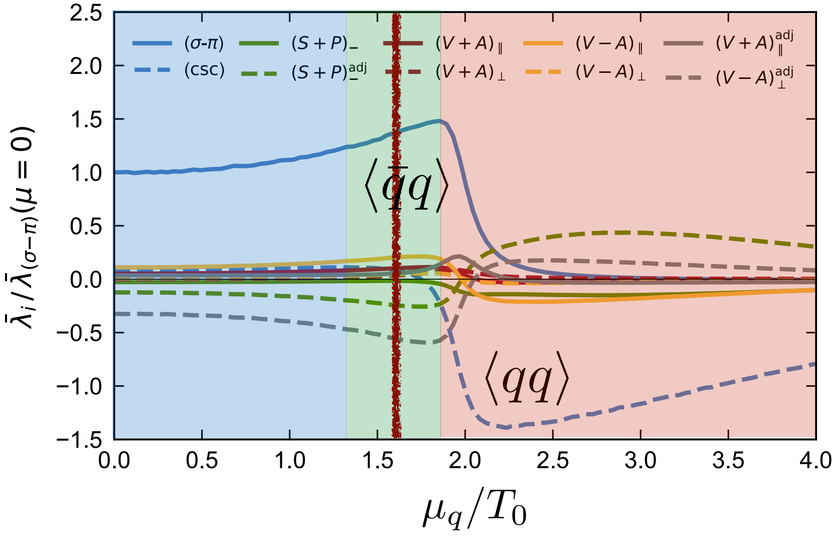
Prediction



Estimate

Regime of quantitative reliability of current best truncation

Emergent diquarks (fRG)

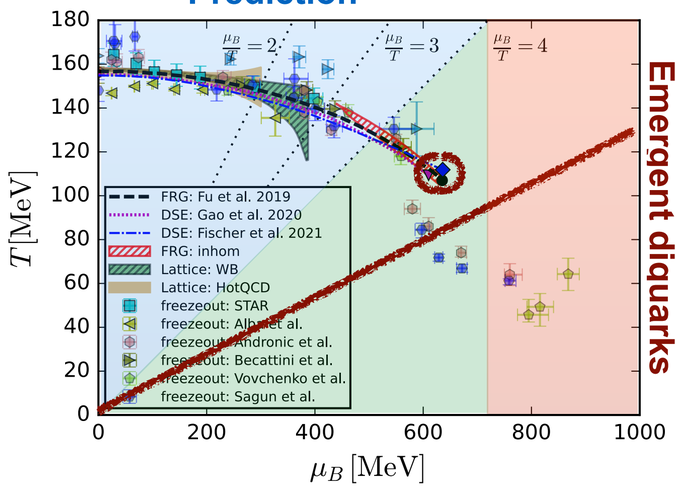


Braun, Leonhardt, Pospiech, PRD 101 (2020) 036004

Predictions & estimates

Emergent diquarks

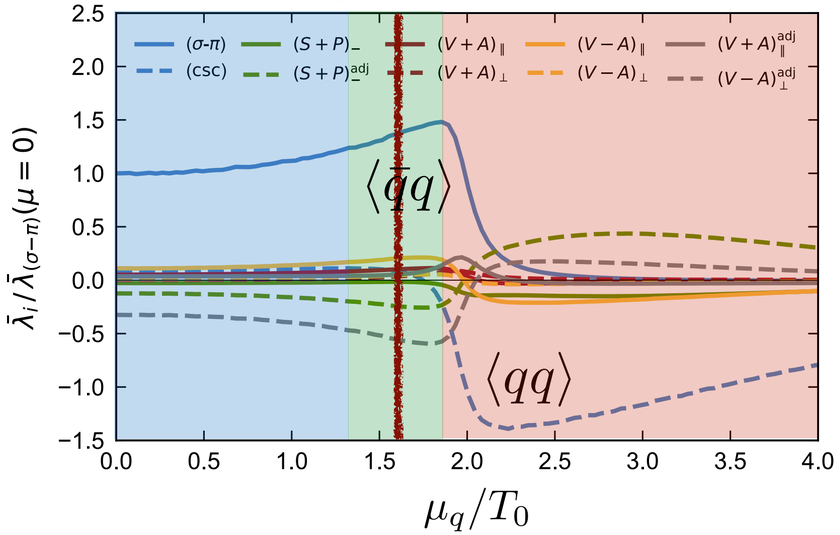
Prediction



Estimate

Regime of quantitative reliability of current best truncation

Emergent diquarks (fRG)



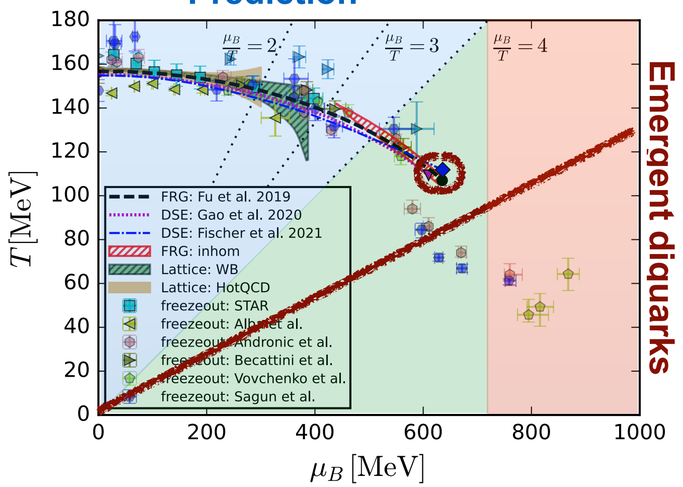
Emergent diquarks are not captured by extrapolations

Braun, Leonhardt, Pospiech, PRD 101 (2020) 036004

Predictions & estimates

Emergent diquarks

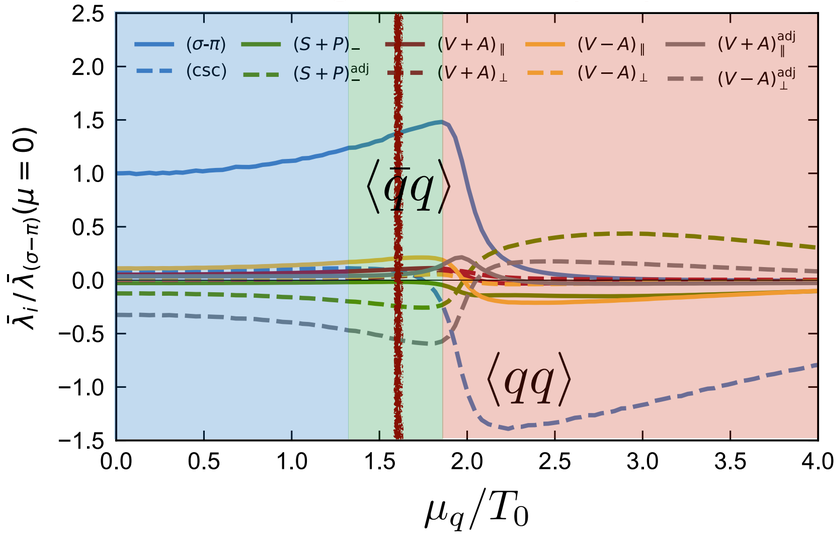
Prediction



Estimate

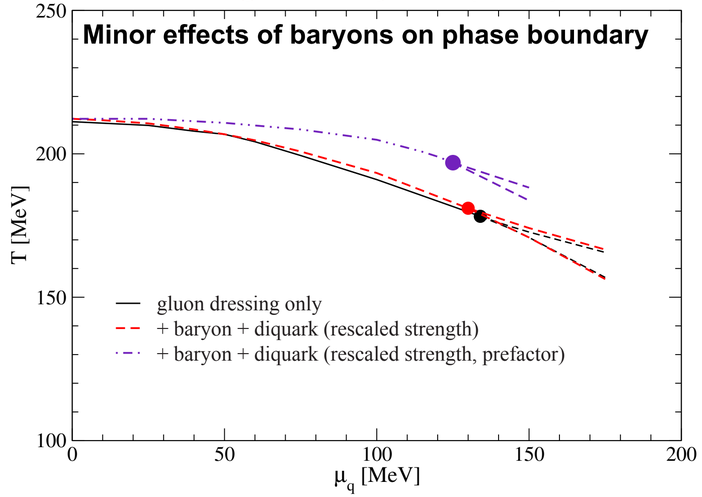
Regime of quantitative reliability of current best truncation

Emergent diquarks (fRG)



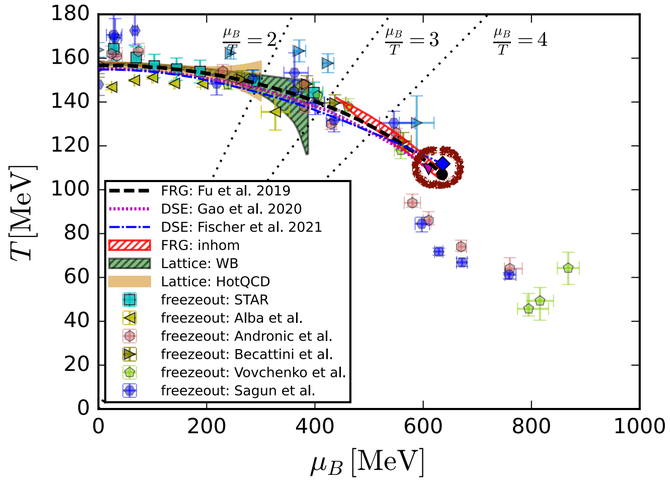
Braun, Leonhardt, Pospiech, PRD 101 (2020) 036004

Emergent baryons (DSE)



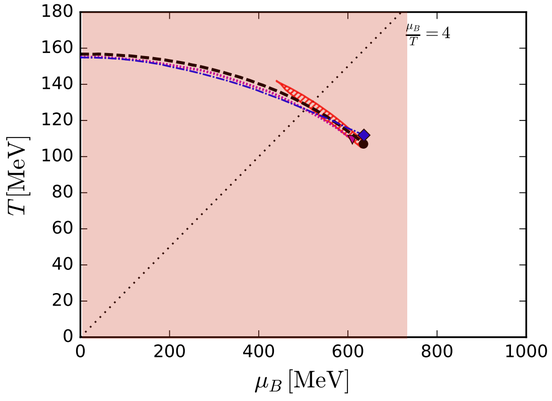
Eichmann, Fischer, Welzbacher, PRD 93 (2016) 034013

Predictions, estimates & extrapolations and how to use them



Scenario I

Scaling

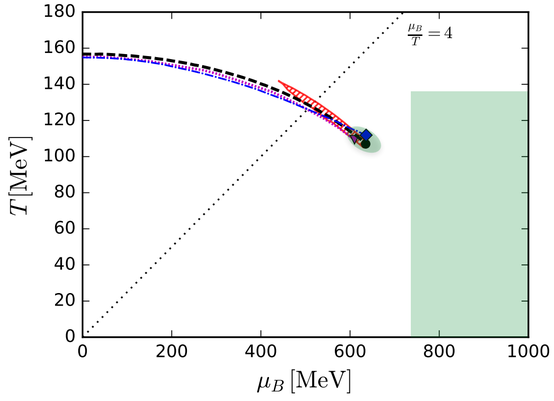


Extrapolations for Pheno

✓

Scenario II

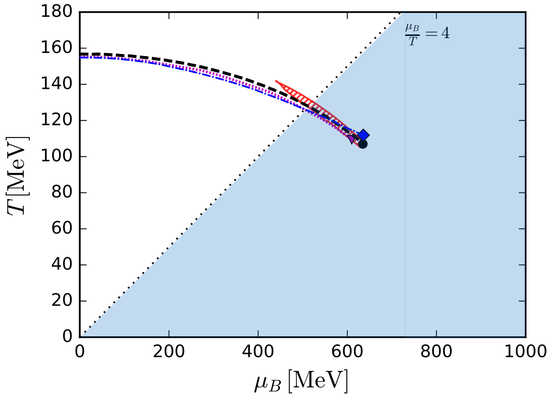
Minimal scaling and new phases



✓

Scenario III

Scaling and/or new phases



✗

Predictions, estimates & extrapolations and how to use them

Out by the LEGO ®principle

Fu, JMP, Rennecke, PRD 101 (2020) 054032

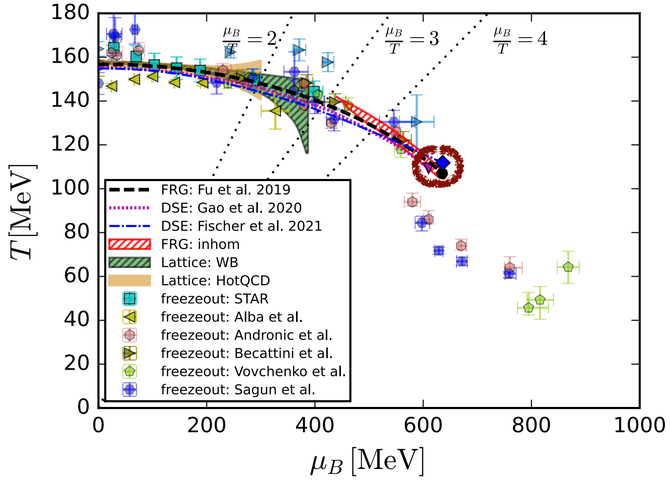
+

Size of scaling regime in LEFTs

Schaefer, Wambach, PRD 75 (2007) 085015

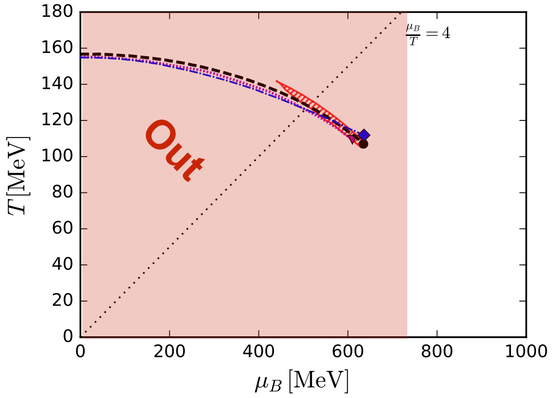
Braun, Klein, Piasecki, EPJC 71 (2011) 1576

⋮



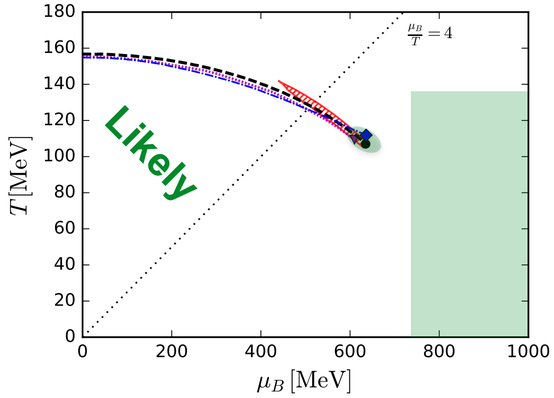
Scenario I

Scaling



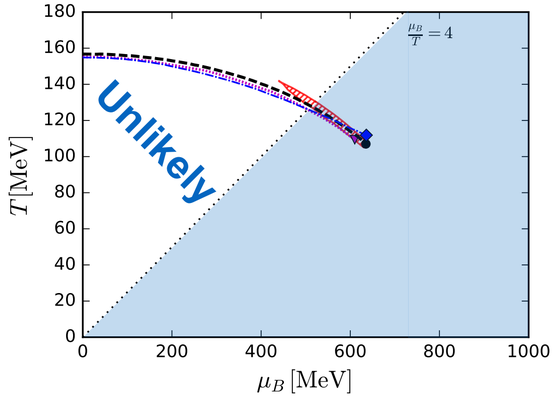
Scenario II

Minimal scaling and new phases



Scenario III

Scaling and/or new phases



Braun, Fu, JMP, Rennecke, Rosenblüh, Yin, PRD 102 (2020) 056010

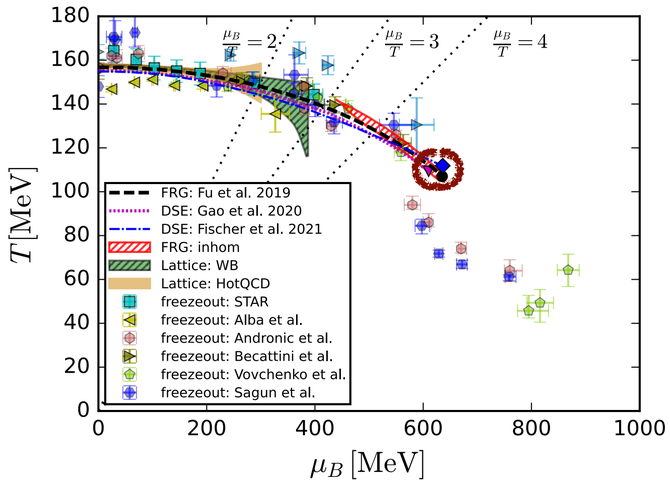
Gao, JMP, PRD 105 (2022) 094020

Soft modes in hot QCD matter: Braun, Chen, Fu, Gao, Huang, Ihssen, JMP, Rennecke, Sattler, Tan, Wen, Yin, arXiv:2310.19853

+ many results in dynamical low energy effective theories

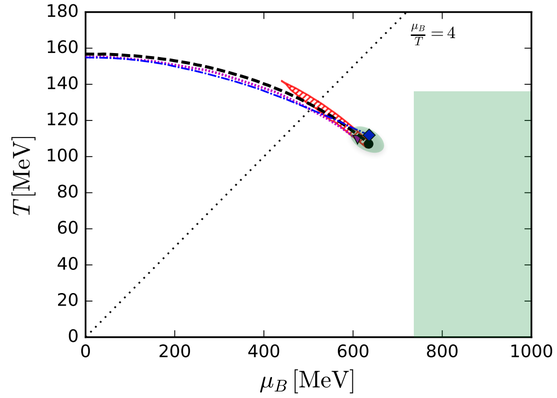
LEGO® principle

Predictions, estimates & extrapolations and how to use them



Scenario II

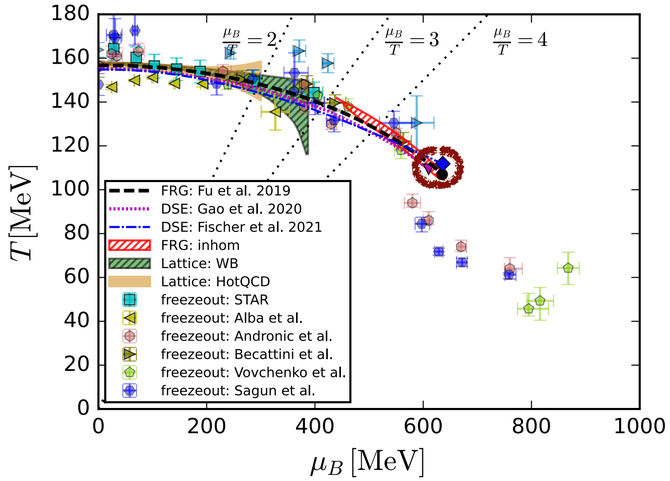
Minimal scaling and new phases



Extrapolations for Pheno

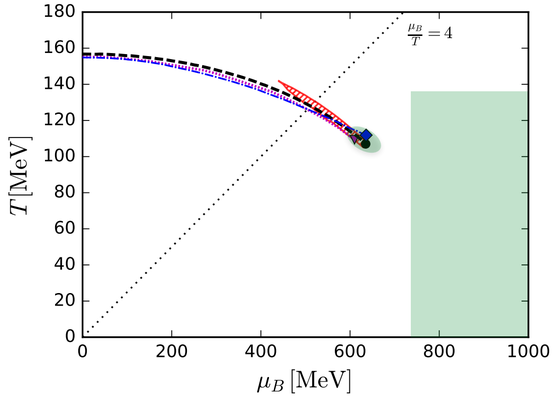
✓

Predictions, estimates & extrapolations and how to use them



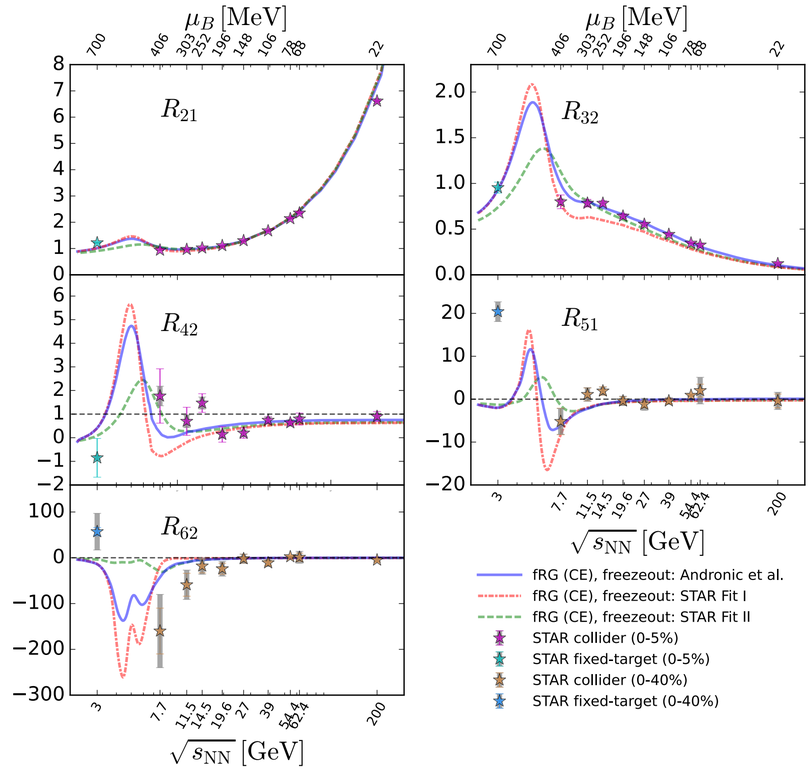
Scenario II

Minimal scaling and new phases



Ripples of the critical end point

baryon & proton number fluctuations



see talk of Wei-jie Fu

Extrapolations for Pheno

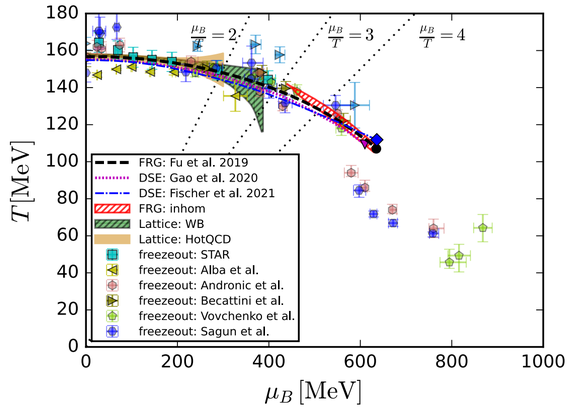
✓

Fu, Luo, JMP, Rennecke, Wen, Yin, arXiv:2308.15508

Summary

fQCD

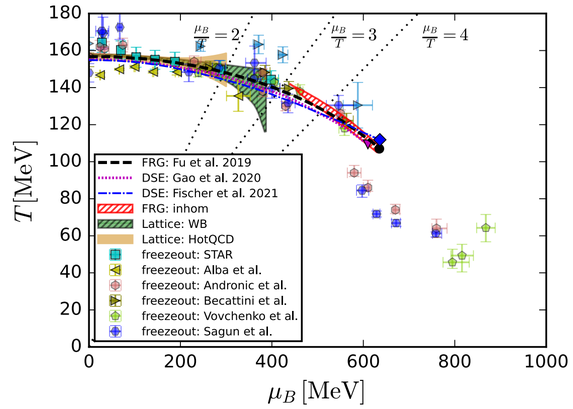
- **Functional QCD provides direct 1st principle results for the phase structure at finite density**
  - **Predictions:** $\frac{\mu_B}{T} \lesssim 4$
  - **Estimates:** $4 \lesssim \frac{\mu_B}{T} \lesssim 8$



Summary

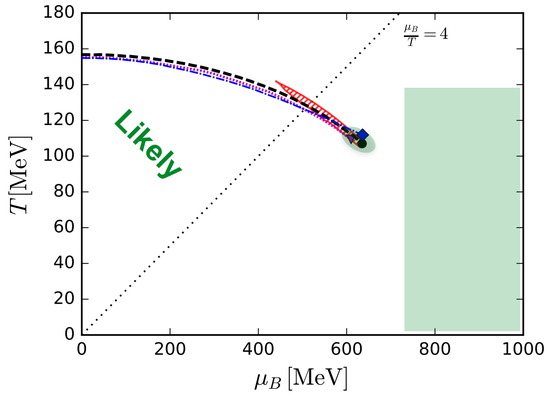
fQCD

- **Functional QCD provides direct 1st principle results for the phase structure at finite density**
  - **Predictions:** $\frac{\mu_B}{T} \lesssim 4$
  - **Estimates:** $4 \lesssim \frac{\mu_B}{T} \lesssim 8$



- **The results support the use of extrapolation approaches for phenomenological applications**
  - **Explanation for the convergence of CEP locations of extrapolation approaches**
  - **Access to observables such as fluctuations of conserved charges**

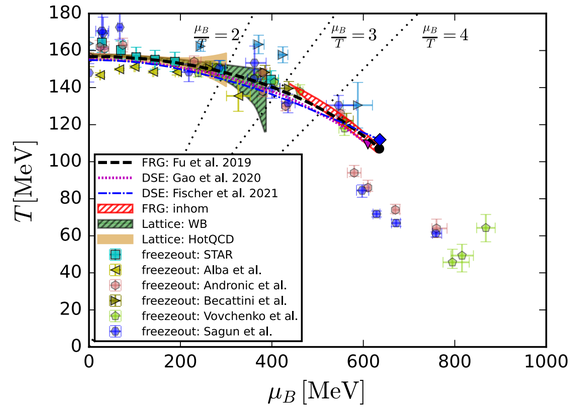
Minimal scaling and new phases



Summary

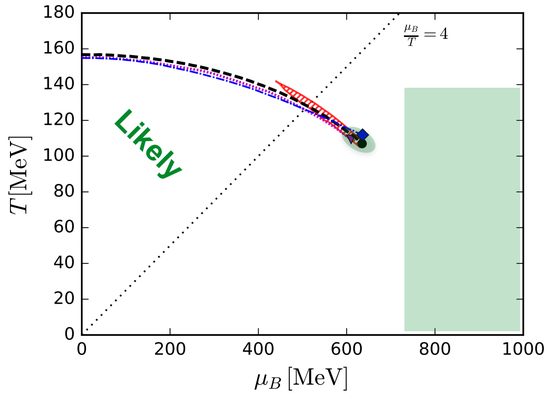
fQCD

- **Functional QCD provides direct 1st principle results for the phase structure at finite density**
  - **Predictions:** $\frac{\mu_B}{T} \lesssim 4$
  - **Estimates:** $4 \lesssim \frac{\mu_B}{T} \lesssim 8$



- **The results support the use of extrapolation approaches for phenomenological applications**
  - **Explanation for the convergence of CEP locations of extrapolation approaches**
  - **Access to observables such as fluctuations of conserved charges**

Minimal scaling and new phases



- **Systematic error estimates with the LEGO® principle**

CEP Estimate → CEP Prediction

Stay tuned

Diquarks/baryons: ✓ **Density channel/mode:** (✓) **Moat/inhomogeneous regime:** ((✓))